FULLY IMPLANTABLE INTEGRATED SILICON BIOTELEMETRY MICROSYSTEMS

Annual Progress Report

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Introduction

This research aims at the development of miniature, totally implantable, multichannel, biotelemetry systems for the measurement of a number of physiological parameters in small unrestrained rodents and primates. Long-term monitoring of a number of physiological parameters in rodents and small primates for a period of several months is of great interest to NASA for both ground-based and future Space Station studies. In particular, reliable measurement of many parameters using a small, totally implantable system suitable for use in small mammals has not been achieved, primarily due to a lack of appropriate sensors, telemetry systems, and signal processing and control electronics. The latter two areas have made significant progress during the past few years as small wireless transceivers are finding their way into many consumer markets, and as microelectronics is continuing its impressive development in implementing low power, high speed, and much more versatile microelectronics chips. It is the first area, i.e., sensor development, and its slow progress which has primarily prevented the development of *miniature, implantable, multi-sensor measurement capsules.*

This research will overcome these shortcomings by applying advanced solid-state sensor technologies based on silicon micromachining to the development of a fully implantable multichannel unit for application in small primates. The implantable unit will be able to measure three axes of acceleration, temperature, multichannel neural signals, and blood pressure from within the body, amplify and buffer these signals, and transmit the information outside through a radio-frequency telemetry link to a range of several feet. The entire system to be developed will incorporate all of the sensors, interface circuits, and wireless communication link in a module with a target volume of less than 5cc and a minimum lifetime of about 3-6 months. The implanted unit will be powered and controlled using miniature batteries, and will communicate with a central data collection station using high-frequency telemetry. The overall architecture of the system in each module will be upgradeable in the future to include other parameters of interest to NASA, such as flow, and chemical species. Most of these parameters can now be reliably and easily measured using silicon-based microsensors and we can include these in future versions of the module. The primary objectives of this proposed research are: 1) the development of miniature multi-sensor measurement units that can interface with the biological environment and record different physiological parameters for extended periods of time; 2) the development and application of silicon micromachining techniques to the fabrication of microstructures and micromechanical systems that are needed in both physical and chemical microsensors; 3) the development of low-power integrated circuits for signal processing, voltage regulation, data modulation and demodulation, analog-digital conversion, and telemetry; 4) the development of suitable micropackaging techniques for protecting the implant from harsh biological environments, and 5) implantation and long-term monitoring of physiological parameters using these fully implantable units in rats for periods of at least several months. Our long-term goal under this research is to push the limits if technology in all areas and, in future projects, implement a multi-sensor, miniature module that is less than 1cc in volume, and can measure a variety of physical and chemical parameters for several months.

Our approach to the implementation of the implantable biotelemetry module is shown in Figure 1. The overall module consists of three major components: 1) the sensor chips each capable of measuring a different parameter or set of parameters; 2) the central data conversion, processing and control electronics; and 3) the telemetry and power management unit. The individual sensor chips may contain on-chip signal processing to amplify and transmit sensor data (either in the form of analog voltage or frequency) over a standardized bus to the central controller. The central controller receives sensor data from different chips, converts the data using an on-chip ADC, digitally compensates for any second-order parameters (such as temperature), and will the transmit the processed sensor data over a telemetry link to the outside world. The bus between the central controller and the individual sensor chips is a standard sensor bus that we have developed under

other related research projects and is a critical aspect of the overall system [1]. This standard bus allows the system to be capable of supporting a number of sensor chips as these chips become available in the future. As was mentioned in the introduction, our immediate goal under this present proposal is to include sensors for the measurement of three axis of acceleration, temperature, neural signals, and blood pressure. However, we believe that for the biotelemetry applications of interest to NASA, many more channels and sensors for the measurement of additional parameters will be added as these become available. The above organization for the system is capable of evolving upward in sophistication in the future as more channels and additional sensors are added to the module.

Summary of Progress During First Year:

In the first year of this project we made progress in several areas. First, we designed, fabricated, and tested a capacitive pressure sensor for our colleagues at NASA Ames, and are in the processing of delivering such pressure sensors for their application for in-vivo monitoring. We also began to define, and design the overall system architecture for the implantable telemetry system. Each of these areas will be described briefly below.

Implantable System:

During the first year of the project we have defined the system architecture and telemetry scheme for a 16 channel modular implantable biotelemetry system. The 16 channel biotelemetry system will accommodate: 8 neural recording channels (5 KHz BW), one temperature channel (0.1 Hz BW), two pressure channels (100 Hz BW), three acceleration channels (100 Hz BW), one EKG/EEG channel (100 Hz BW), and one synchronization channel. These channel assignments are made according to the experimental requirements reported in "Animal Biotelemetry System Feasibility Study" prepared by NASA Ames. These parameters will be measured for 5 minutes every hour during the day.

To power the implantable units we will use Duracell lithium batteries in a size appropriate to our package have a voltage and capacity of 3 V and 250 or 500 mAHour. Therefore, the total power drain of the system should remain below 2.5 mA when making measurements (using two 3 Volt, 500 mAHour batteries in series). The biotelemetry system will be 5cc in volume and should operate for a total of 200 hours.

Recorded sensor signals will be first amplified, and then digitized using an on-chip low-power analog-digital converter before transmission to the outside world using a separate on-chip transmitter. Because of the low-power requirements of the system, careful attention has to be paid to the design of the on-chip circuitry, especially the AD converter. We are currently considering different designs for the AD converter circuitry. The two most suitable approaches to the design of this block include a successive approximation scheme and a pipelining AD converter. During the second year of the project we will perform simulation and analysis of these two approaches and will choose the most appropriate design.

Once the data is converted into a digital format, it will transmitted to the outside world using RF telemetry. The biotelemetry frequency band of 175-216 MHz has been chosen for the system. This frequency band is high enough to allow adequate miniaturization of the transmitter while accommodating the required bandwidth of the transmission (1 Mbps). In addition, this frequency band is wide enough for assigning various transmission frequencies to different animals for frequency division multiple access (FDMA). Each implant will have its own transmission frequency which is set using an on-chip capacitor. The transmitter is a simple Colpitts oscillator which used a single transistor and a number of resistors and trimmable capacitors. In order to

reduce the size of the transmitter, all the components except for the transistor will be integrated on a single silicon chip, which will then later support the hybrid surface mount transistor, as shown in Figure 2. The frequency of the transmitter can be trimmed by changing the value of the oscillator capacitor. We have already built a hybrid oscillator using discrete components and have demonstrated that the oscillator frequency remains stable to better than 2% over temperature. This is very adequate for this application which requires a small range. This design will be further optimized in the coming year.
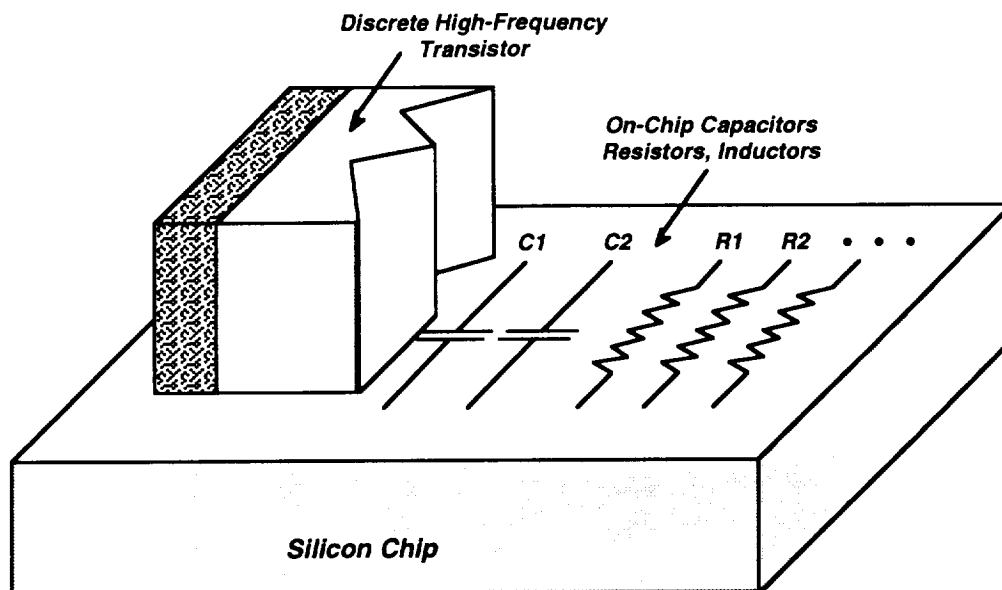

Figure 2: Structure of the miniature Colpitts transmitter for use with the implant.

The telemetry modulation scheme of pulse code modulation (PCM)/amplitude shift keying (ASK) was chosen for the implantable system. This choice was made based on four factors: 1) power consumption; 2) simplicity of implementation; 3) bandwidth; and 4) possibility of further expansions and modifications if needed. The reduction of the system power consumption is the most important factor with regards to the first modulation method. Although pulse position modulation (PPM) has a lower power consumption than pulse code modulation (PCM) if used with a low duty cycle, in order to keep the system versatile for future modifications and expansions, PCM was chosen over PPM for the system. The choice of amplitude shift keying (ASK) over frequency shift keying (FSK) and other modulation schemes for the final transmission was made primarily due to the simplicity of implementation and detection. This is in spite of the fact that FSK has a better S/N ratio and is often used in biotelemetry applications. Although more advanced modulation schemes like: Quadrature Amplitude Modulation (QAM), and Quadrature Phase Shift Keying (QPSK) exist that can achieve lower power consumption and error rate; they require more sophisticated transmitter and receiver circuitry.

In summary, in the first year of the project, we have defined the system architecture, have chosen the set of physiologic parameters to be measured, have determined the transmitter structure and the data modulation scheme, and have also considered various packaging schemes for the overall implant. The packaging approach is not discussed here and is still under review at the time of the writing of this report.

Development of an Implantable Pressure Sensor:

During the early part of this project, we undertook a major activity which was not stated in our original statement of work. This change was in part encouraged by our NASA project monitor and in part by the need of the research group at NASA Ames for a stable implantable miniature pressure sensor for monitoring intrauterine pressure (IUP) during labor. Obviously this undertaking took away some effort from some of the other tasks of the project. We have now completed the design, fabrication, and testing of the pressure sensor and hope to be able to deliver it to our colleagues at NASA Ames.

These pressure sensors were developed in response to the need for a small, low-drift, low-power pressure sensor. Based on the basic characteristics of intrauterine pressure (5-15 mmHg resting pressure having strong fluctuations between 30 to 100 mmHg during early labor and second stage respectively) we designed a capacitive pressure sensor to achieve the functional characteristics shown in Table 1.

Table 1: A summary of important characteristics of an IUP pressure sensor

Dynamic range	Resolution	Sensitivity	Drift	Dimensions
0-100 mmHg	1 mmHg	~1 fF/mmHg	< 3mmHg/month	Diam. < 750 μm

Capacitive pressure sensors are attractive due to their increased sensitivity and reduced power consumption compared to the more traditional piezoresistive pressure transducers. Based on the required characteristics of the IUP pressure sensor a capacitive transducer was designed with the calculated performances shown in Table 2. Since the capacitance variation of the transducer is a few fF, there is a need for a hybrid readout circuitry close to the sensor. We have used a switched-capacitor charge integrator that was designed under another project. This circuit converts the capacitance variations of the sensor to voltage variations and provides a low output impedance. This circuit is very tolerant of input parasitic capacitance and consumes ~300μA.

Table 2: Designed characteristics of the capacitive pressure transducer.

Dynamic Range	0-100 mmHg
Resolution	1 mmHg
Sensitivity (at C_0)	1 fF/mmHg
Touching Pressure	150 mmHg
Diaphragm Diameter	550 μm
Metal Plate diameter	350 μm
Diaphragm Thickness	2.5 μm
Plate Separation	2 μm
C_0	425 fF
ΔC (full scale)	130 fF

Figure 3 shows a photograph of a fabricated pressure sensor chip. The chip contains two circular diaphragms, one is a reference capacitor and the other is the variable capacitance. Both of these sensors are supported on a glass substrate. After fabrication, the pressure transducers were tested for functionality and characterization. First a set of electrostatic tests were performed to measure the pull-in voltage. Then the devices were mounted on a PC board and sealed in atmosphere with Torrseal@. A preliminary set of measurements were performed without the interface circuitry and the capacitance variations were measured vs. applied pressure. The interface circuitry was then mounted with the pressure sensor on the same PC board and a complete set of measurements were performed. Tables 3 summarizes the calibration test results. In addition to the pressure sensor developed for monitoring intrauterine activity during labor, we designed and fabricated other miniature pressure transducers to be incorporated in our future telemetry module for measuring blood pressure from outside of the vessel. These sensors are based on extra-vascular tonometric method of measuring BP. Using this method one can measure BP without the need for invading the vessel with a catheter. We are in the process of characterizing these sensors and having them available to be used in our system.
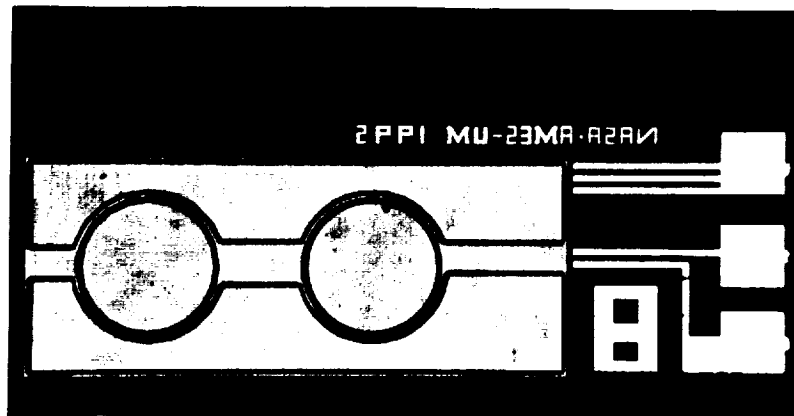

Figure 3: Photograph of a fabricated capacitive pressure sensor chip.

Table 3: A summary of pressure chamber measurements with interface circuitry.

ΔV(FSO)	125 mV
Accuracy	0.4 %
Linearity	5 %FSO
Hysteresis	2.4 %FSO
Resolution	1 mmHg
Sensitivity	0.9 mV/mmHg
TCO	50 mV/°C

Bibliography:

[1] A. Mason, N. Yazdi, K. Najafi, and K.D. Wise, "A Low-Power Wireless Microinstrumentation System for Environmental Monitoring," Digets, Int. Conf. on Solid-State Sensors and Actuators, Transducers '95, Stockholm, Sweden, June 1995